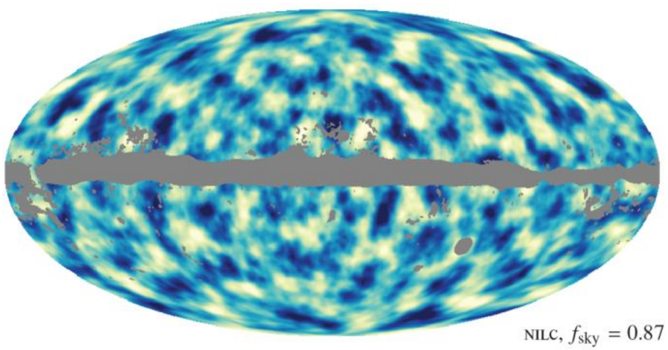
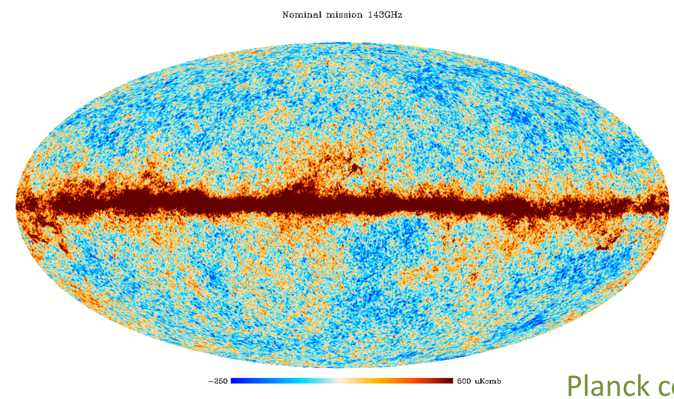
LSS-CMB Correlations





Planck collaboration 2013

University of Sussex

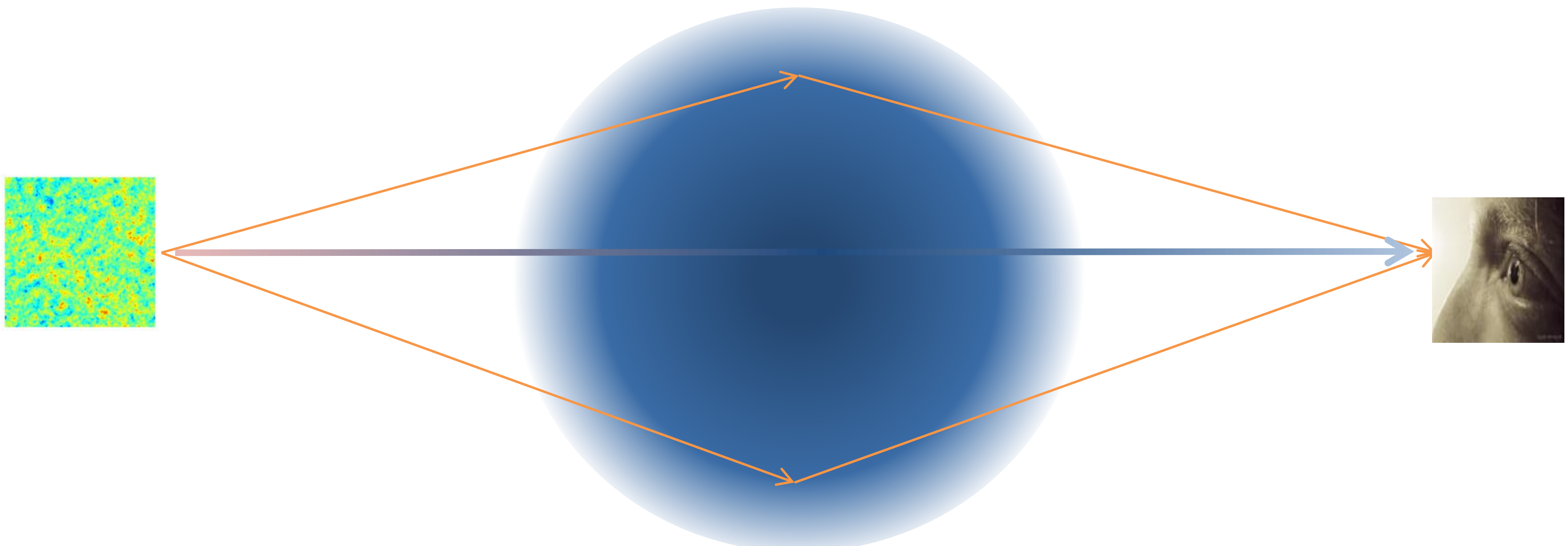
Antony Lewis
http://cosmologist.info/

CMB-LSS correlations

- T Δ_N
- TTΔ_N, TT-CIB
- TTT
- EΔ_N, ETT
- TΔ_b, EΔ_b

$C_l^{T\Delta}$: Well-known ISW correlation between LSS and CMB temperature

$$\Delta T_{\rm ISW}(\hat{\mathbf{n}}) = 2\int_0^{\chi_*} \mathrm{d}\chi\, \dot{\Psi}(\chi\hat{\mathbf{n}}; \eta_0 - \chi).$$



Overdensity: correlated with positive Integrated Sachs-Wolfe (net blueshift)

Underdensity: correlated with negative Integrated Sachs-Wolfe (net redshift)

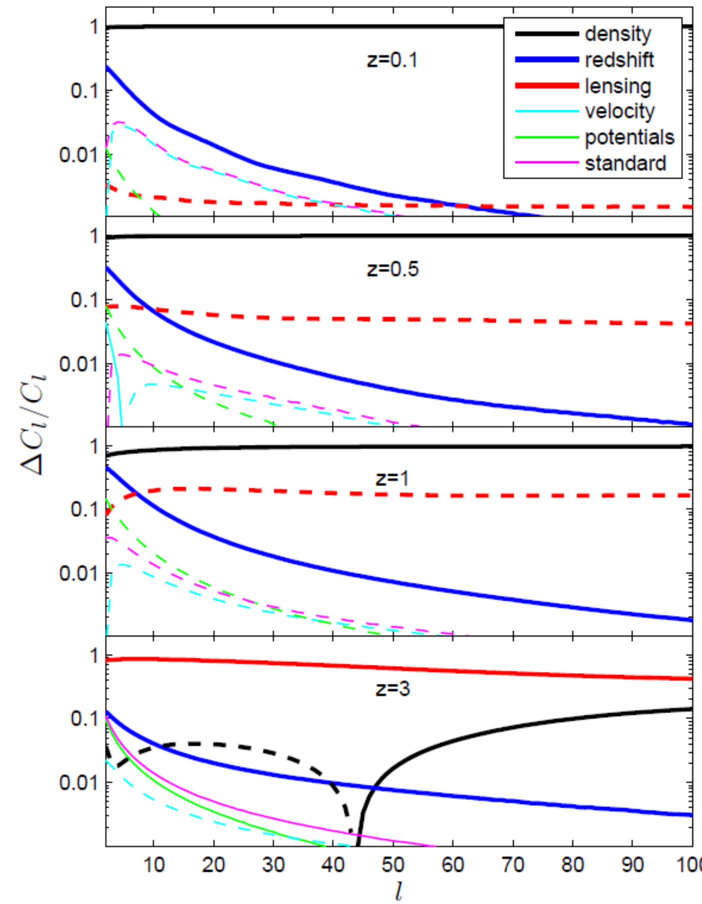
Crittenden & Turok (1996)

The linear power spectrum of observed source number counts

Anthony Challinor[1,2] and Antony Lewis[3,1,*]

$$\Delta_N(\hat{\mathbf{n}}, z, m < m_*) = \delta_N(L > \bar{L}_{s*}) - \frac{1}{\mathcal{H}}\hat{\mathbf{n}} \cdot \frac{\partial \mathbf{v}}{\partial \chi} + (5s-2)\left[\kappa - \frac{1}{\chi}\int^{\eta_A}(\phi + \psi)\mathrm{d}\eta\right]$$
$$+ \left[\frac{2-5s}{\mathcal{H}\chi} + 5s - \frac{\partial \ln[a^3 \bar{N}(L > \bar{L}_{s*})]}{\mathcal{H}\partial\eta} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right]\left[\psi + \int^{\eta_A}(\dot{\phi} + \dot{\psi})\mathrm{d}\eta - \hat{\mathbf{n}} \cdot \mathbf{v}\right] + \frac{1}{\mathcal{H}}\dot{\phi} + \psi + (5s-2)\phi.$$

Full GR calculation of observed galaxy counts as a function of angle and redshift, with bias and magnification bias



- Velocity
- Gravitational potential
- Source evolution
- Lensing
- Correct definition of bias on horizon scales
- Correlation to CMB temperature, polarization
- Numerical code, CAMB sources
  http://camb.info/sources/

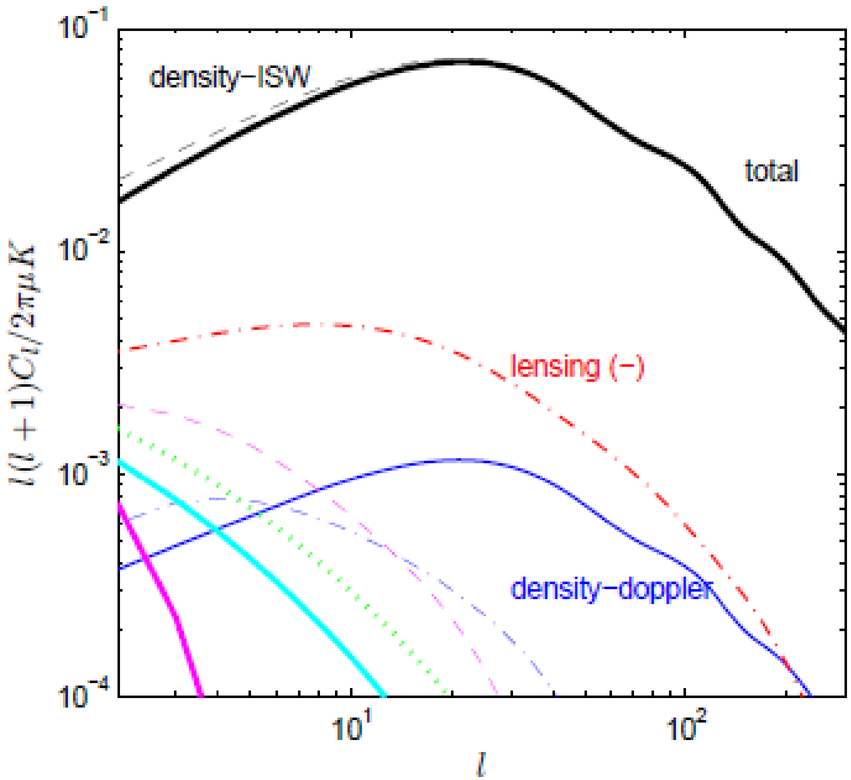
(+linear 21cm, galaxy lensing, and all cross-correlations
+perturbed recombination)

arXiv: 1105.5292 See also Yoo et al, Bonvin & Durrer.

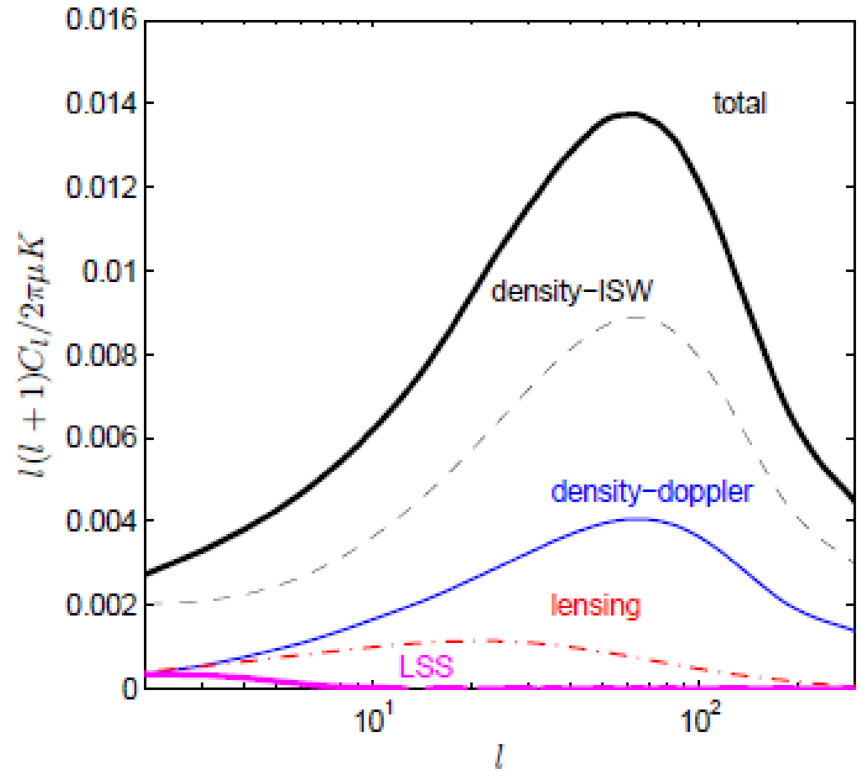
CMB temperature – number counts correlation

$$\Delta_T(\hat{\mathbf{n}}) \approx \int^{\eta_A} \mathrm{d}\eta\, e^{-\tau}\left(\dot{\tau}\hat{\mathbf{n}}\cdot\mathbf{v} + \dot{\psi} + \dot{\phi}\right) \quad \times \quad \Delta_N(\hat{\mathbf{n}}, z, m < m_*) \approx \delta_N - \frac{1}{\mathcal{H}}\hat{\mathbf{n}}\cdot\frac{\partial \mathbf{v}}{\partial \chi} - \left(\kappa + \frac{\hat{\mathbf{n}}\cdot[\mathbf{v} - \mathbf{v}_{oA}]}{\mathcal{H}\chi}\right)(2 - 5s).$$

+ other terms



Z=0.6, $\sigma_z = 0.05, b = 1, s = 0$



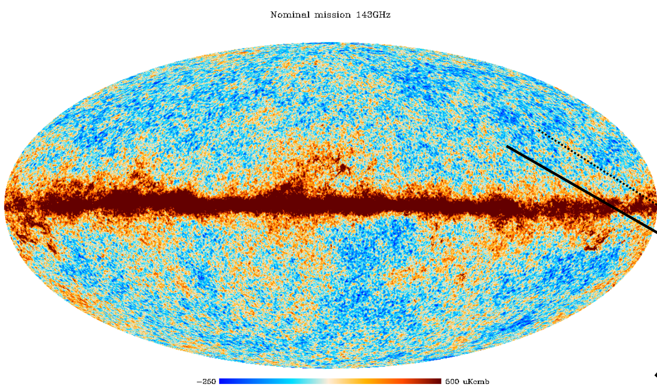
Z=3, $\sigma_z = 0.2, b = 2, s = 0.42$

(note: redshift distortion correlation almost exactly cancels)

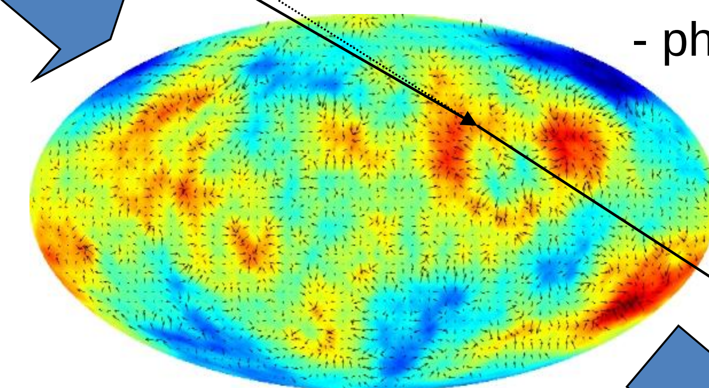
See also Giannantonio et al (2007), Lo Verde et al (2006)

TT as a probe of Large Scale Structure

Weak lensing of the CMB



Last scattering surface



Inhomogeneous universe
- photons deflected

Observer

$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}') = T(\hat{\mathbf{n}} + \boldsymbol{\alpha})$$

$$\boldsymbol{\alpha} = \nabla\psi$$

$$\psi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} \mathrm{d}\chi\, \Psi(\chi\hat{\mathbf{n}};\eta_0 - \chi)\,\frac{f_K(\chi^* - \chi)}{f_K(\chi^*)f_K(\chi)}$$

Non-Gaussianity/statistical anisotropy

reconstructing the lensing field

Marginalized over (unobservable) lensing field:

$$T \sim \int P(T,\psi)\,d\psi$$

- Non-Gaussian statistically isotropic temperature distribution

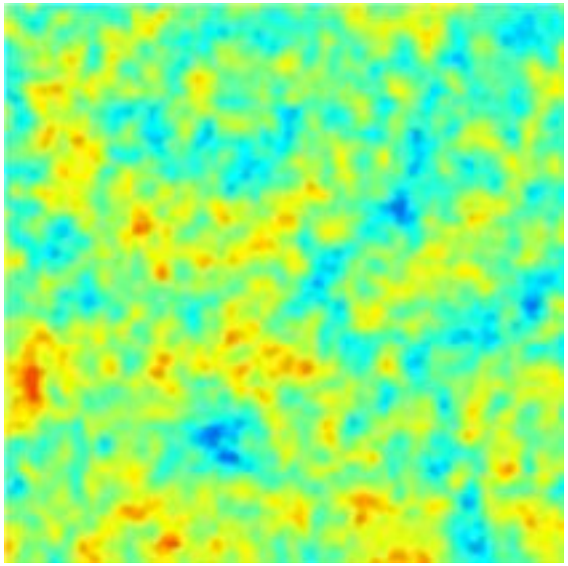
For a given lensing field :

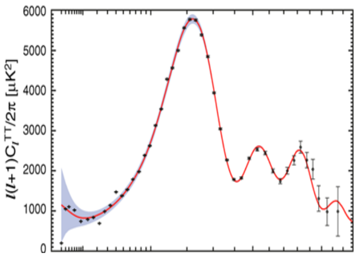
$$T \sim P(T|\psi)$$

- Anisotropic Gaussian temperature distribution

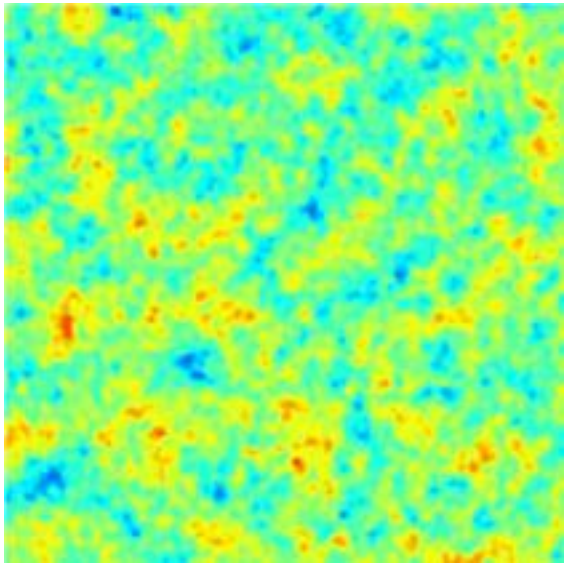
Fractional magnification ~ convergence $\kappa = -\boldsymbol{\nabla} \cdot \boldsymbol{\alpha}/2$

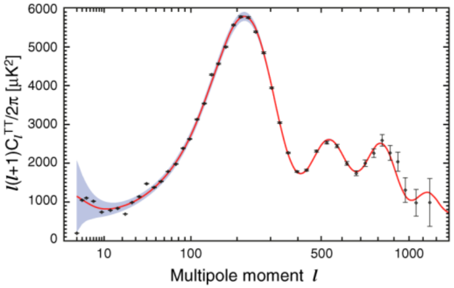
Magnified



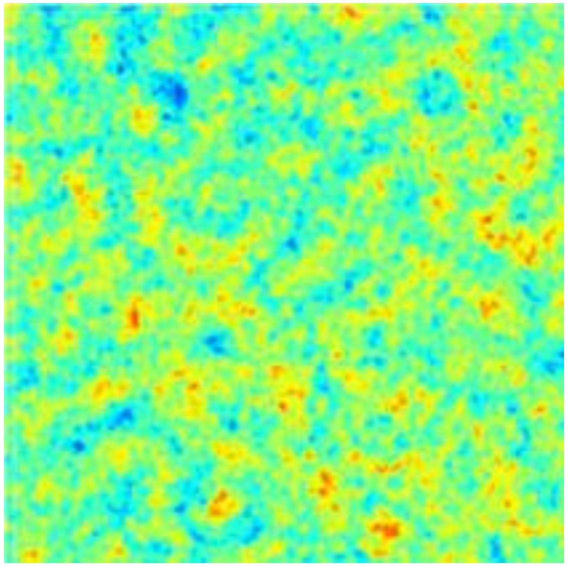


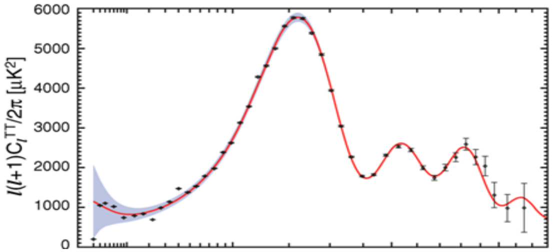
Unlensed





Demagnified





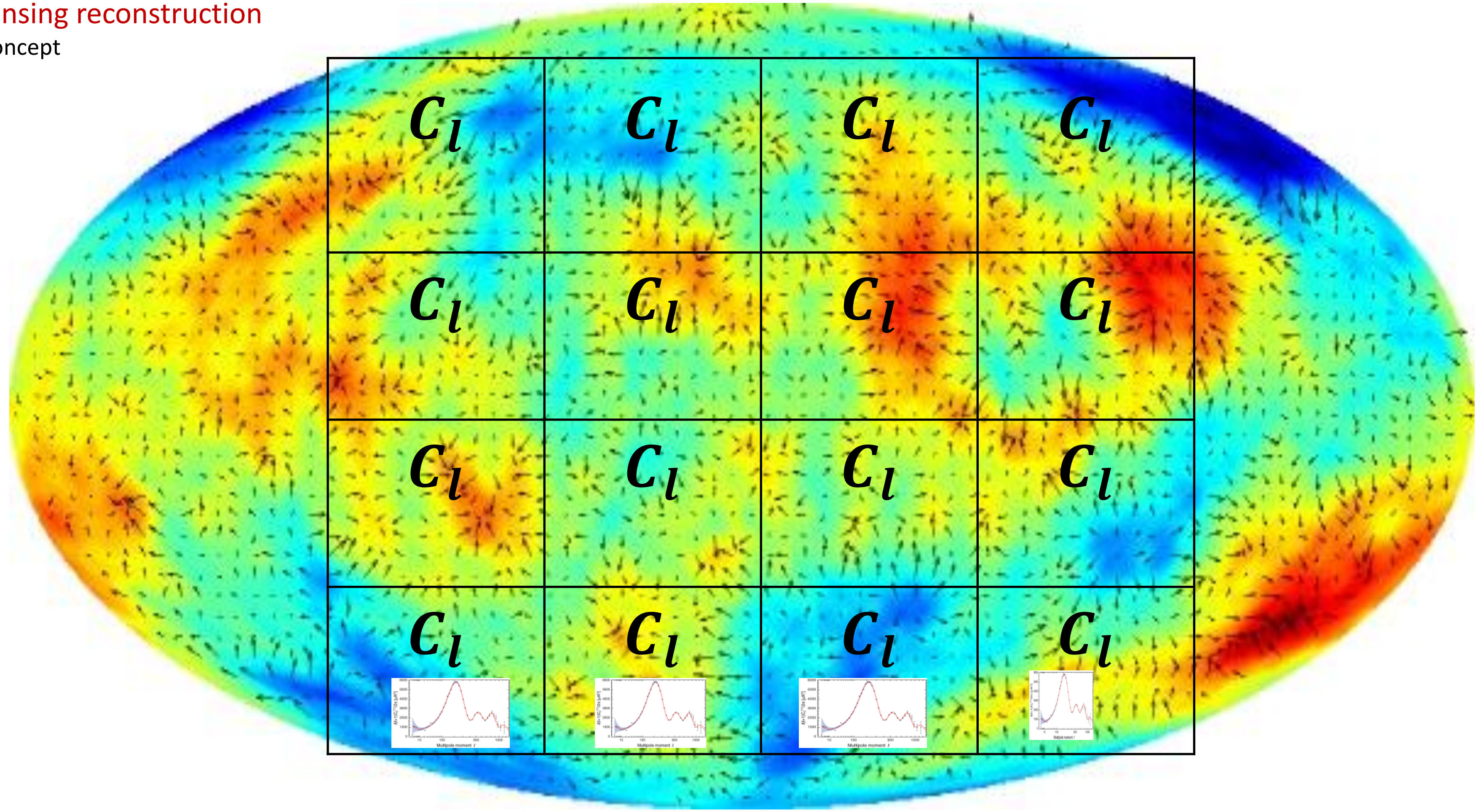
+ shear modulation

$$\langle \tilde{T}(\mathbf{l}_2)\tilde{T}(\mathbf{l}_3)\rangle = C_{l_2}^{TT}\,\delta(\mathbf{l}_2+\mathbf{l}_3)\left[1 + \kappa\frac{\mathrm{d}\ln(l_2^2 C_{l_2}^{TT})}{\mathrm{d}\ln l_2} + \hat{\mathbf{l}}_2^T\gamma\hat{\mathbf{l}}_2\frac{\mathrm{d}\ln C_{l_2}^{TT}}{\mathrm{d}\ln l_2}\right]$$

e.g. Bucher et al

Lensing reconstruction

-concept



Variance in each C_l measurement $\propto 1/N_{\mathrm{modes}}$

$N_{\mathrm{modes}} \propto l_{\mathrm{max}}^2$ - dominated by smallest scales

$\Rightarrow$ measurement of angular scale ($\Rightarrow \kappa$) in each box nearly independent

$\Rightarrow$ Uncorrelated variance on estimate of magnificantion κ in each box

$\Rightarrow$ Nearly white 'reconstruction noise' $N_l^{(0)}$ on κ , with $N_l^{(0)} \propto 1/l_{\mathrm{max}}^2$

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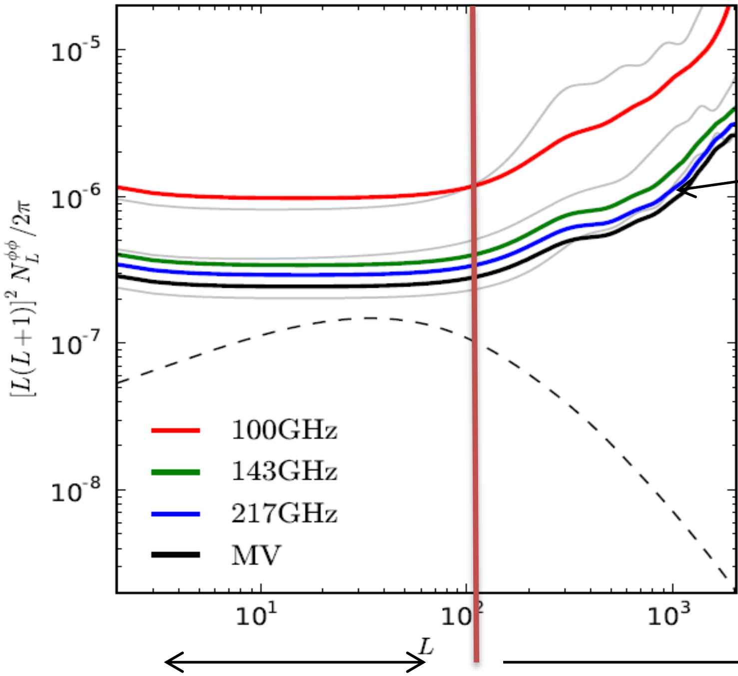


Reconstruction Noise

$N_l^{(0)}$

$\propto C_l^{\kappa} \leftarrow$

$N_l^{(0)} \sim$ const

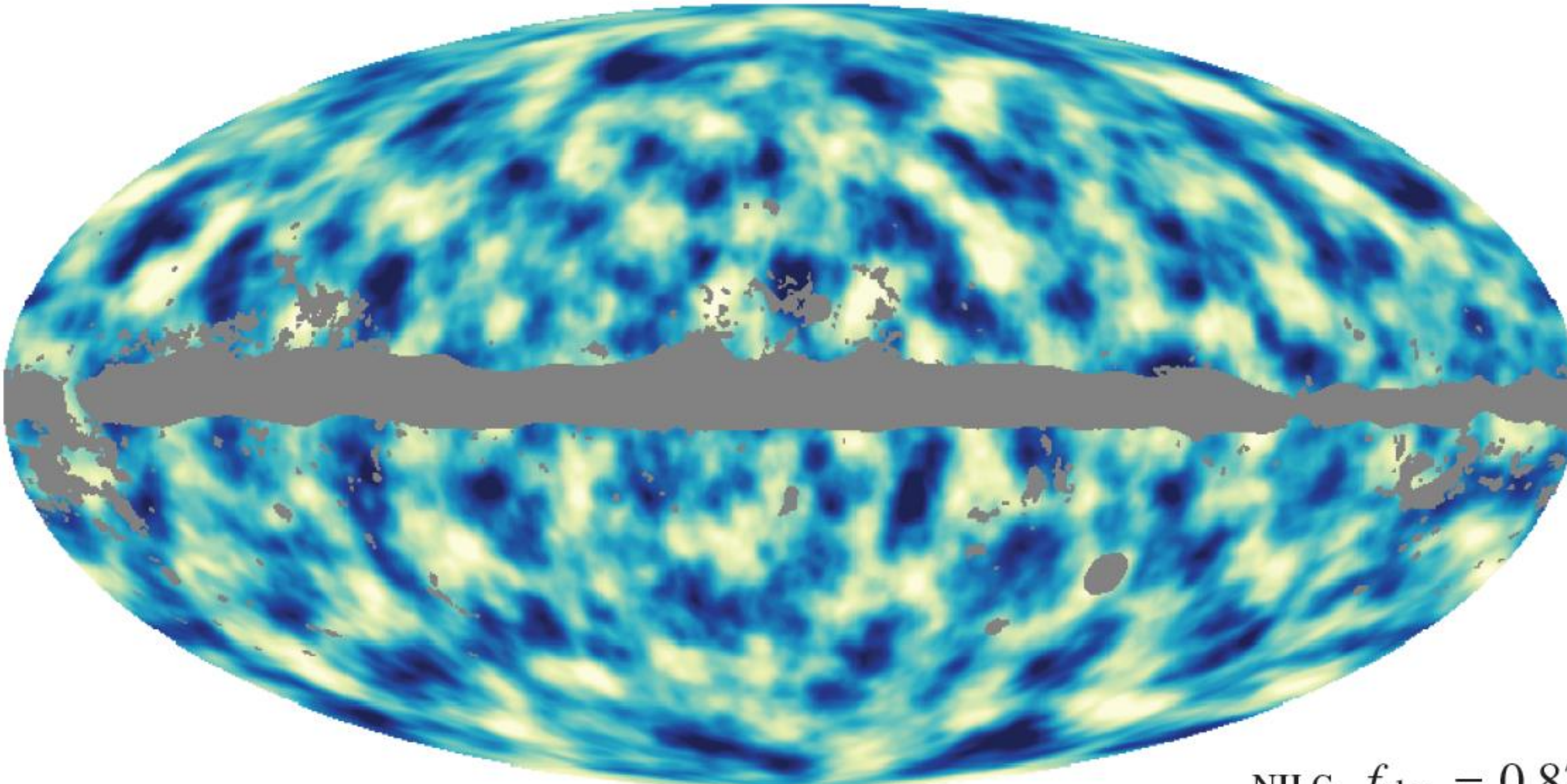
Beam, noise, shape of C_l and $l \sim l_{\max}$ effects

Lensing reconstruction information mostly in the *smallest scales* observed

- Need high resolution and sensitivity
- Almost totally insensitive to large-scale T (so only *small-scale* foregrounds an issue)

- Use separate frequencies and check consistency
- Combine (Minimum Variance – MV) for best estimate
- Also cross-check with foreground cleaned maps

Planck full-sky lensing potential reconstruction: map of integrated LSS at $0.5 < z < 6$



NILC, $f_{\rm sky} = 0.87$

Note – about half signal, half noise,
not all structures are real: map is effectively Wiener filtered

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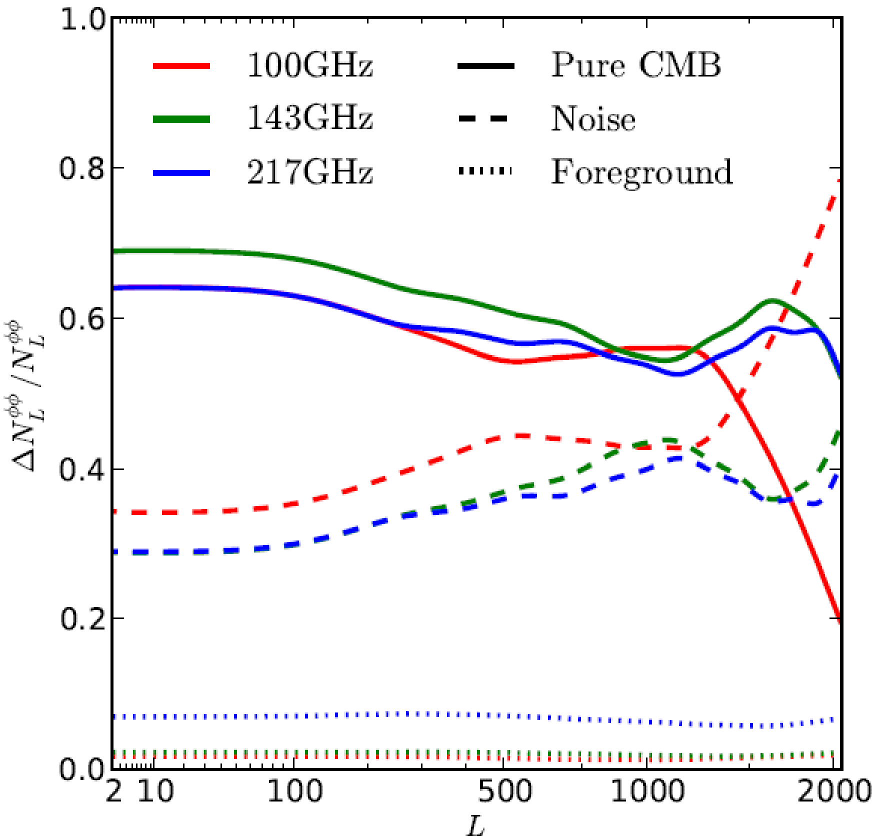
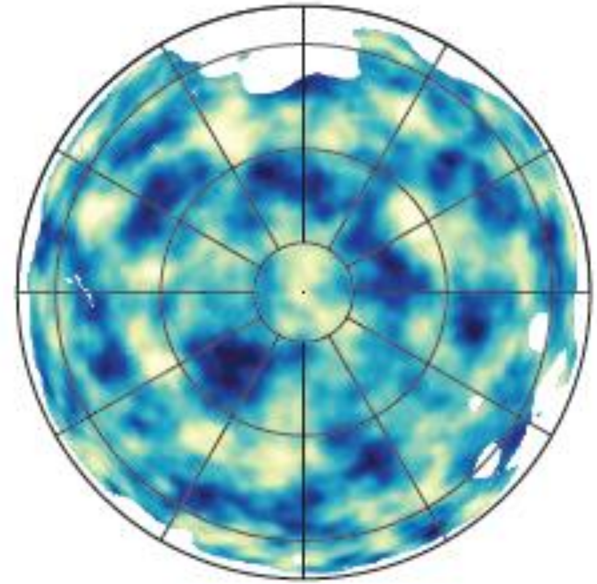
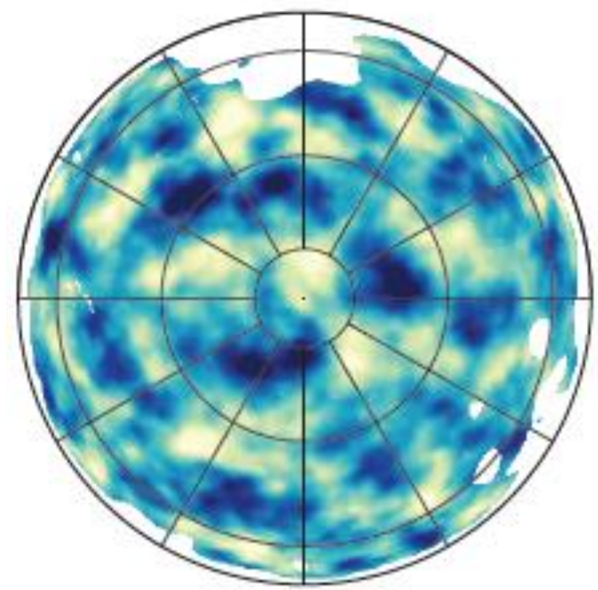
Reconstruction noise budget

Lensing maps are reconstruction noise dominated, but maps from different channels are similar because mainly the same CMB cosmic variance.





Galactic South - 143 GHz



Galactic South - 217 GHz

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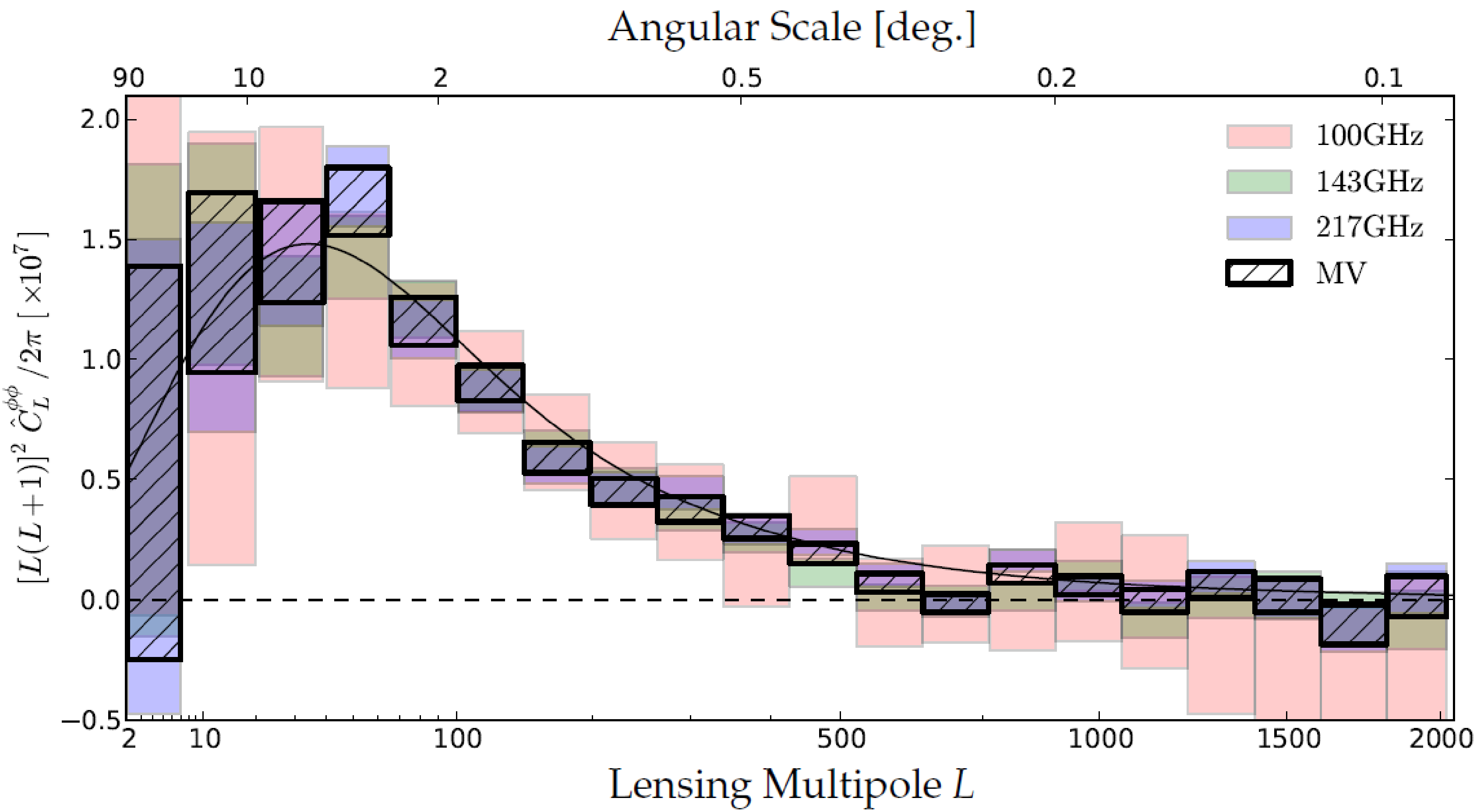
Power spectrum of reconstruction $TT \times TT \ \Rightarrow C_l^{\psi\psi}$



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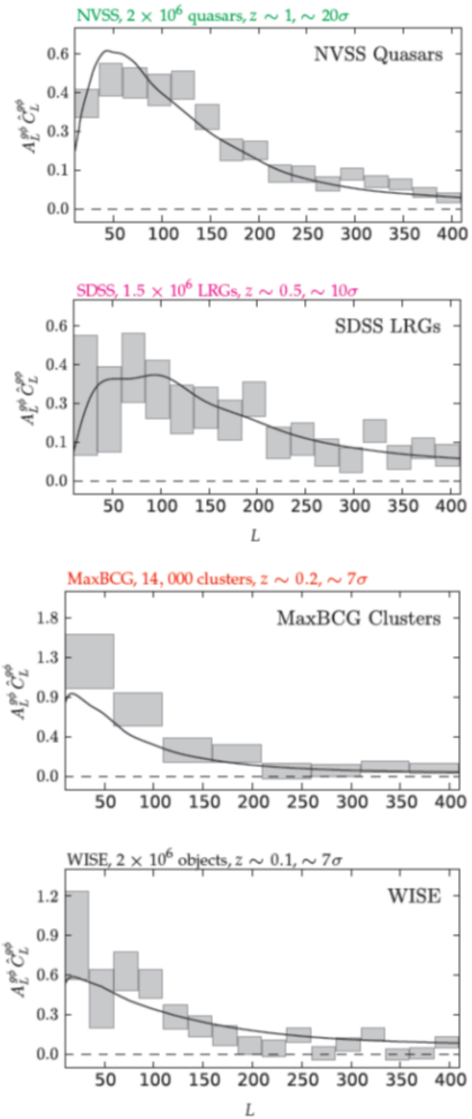
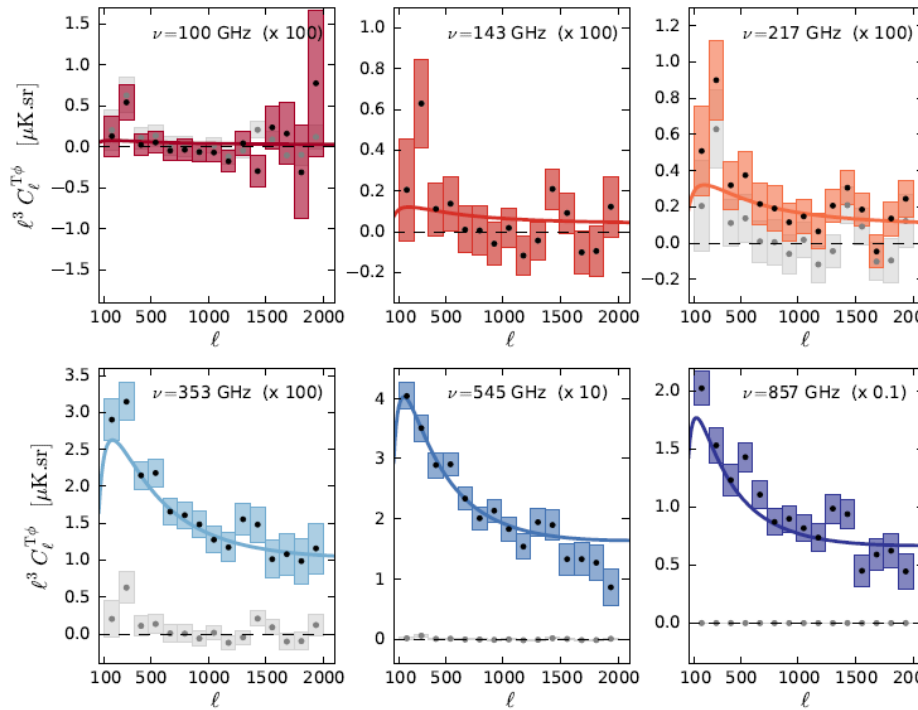
Lensing (TT) × LSS

TT × counts



TT × CIB (*Planck* internal)



> 50σ detection

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TTT: Correlation between lenses and CMB temperature, $C_l^{T\psi}$?

- The late Integrated Sachs Wolfe effect (late ISW) at low redshift from decaying potentials

+

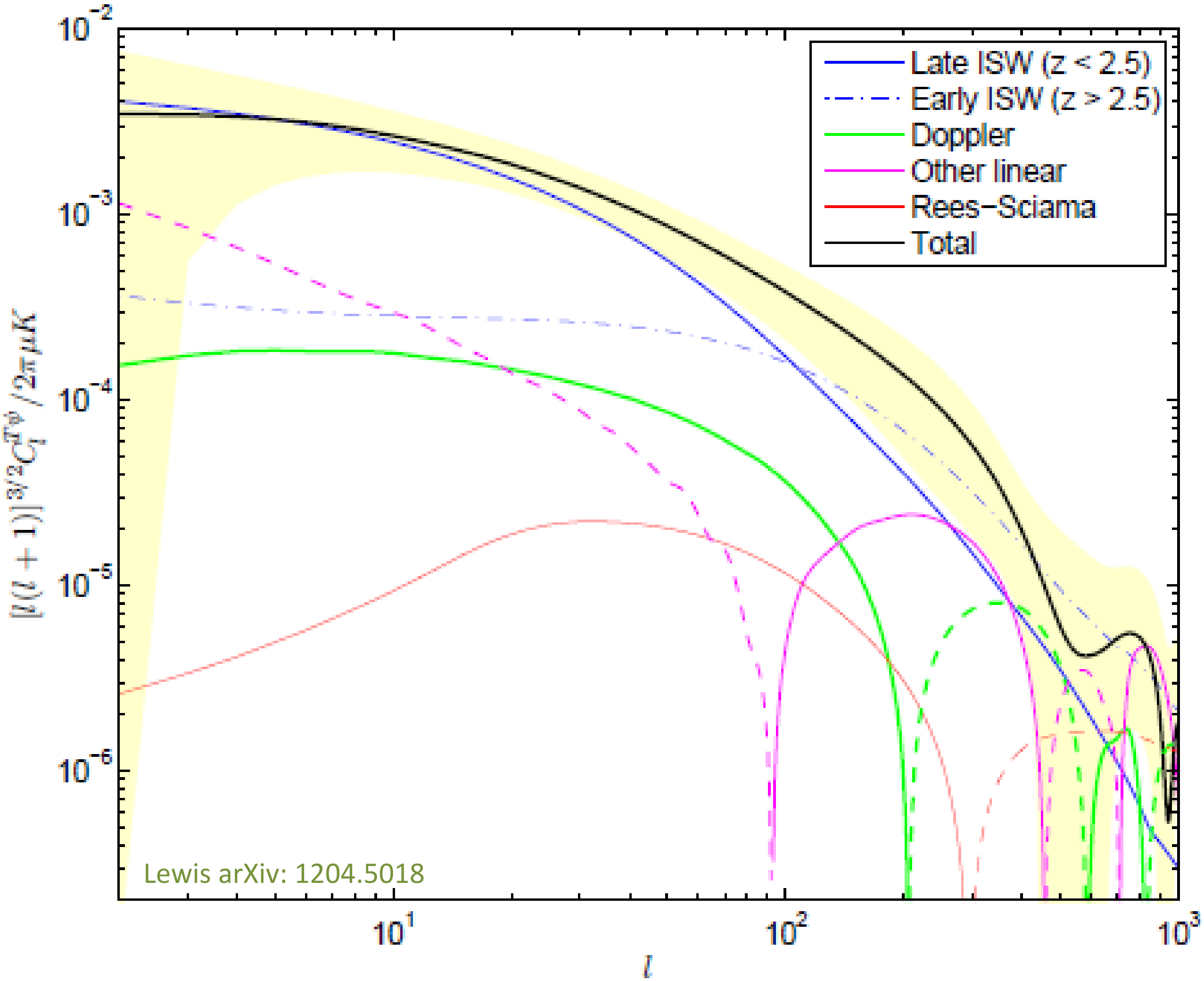
- Large-scale modes that span recombination and also act as lenses
- The early Integrated Sachs Wolfe effect (early ISW) due to the transition from radiation to matter domination, and decaying modes
- Lenses close to last-scattering being correlated to density perturbations that have infall giving a Doppler signal in the CMB
- Doppler signal from scattering at reionization
- Lenses at last-scattering that directly correlate perturbations to lensing at the recombination surface
- Non-linear Rees-Sciama signal at low redshift from non-linear gravitational clustering
- Non-linear SZ signal from scattering in clusters
- Correlations due to foreground contaminants

Linear effects,
All included in self-consistent
linear calculation with CAMB

Non-linear growth effect
- estimate using e.g. Halofit

Potentially important,
but frequency dependent
- ‘foregrounds’, e.g. CIB

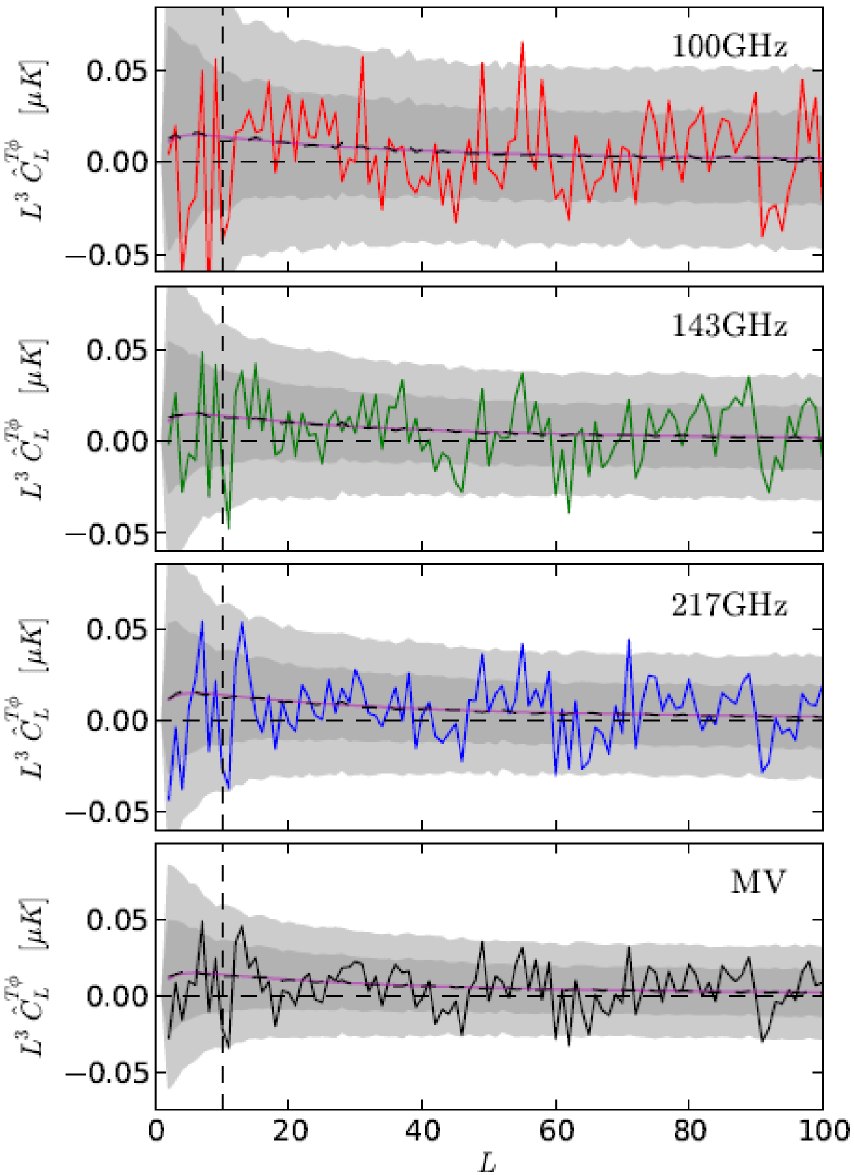
Contributions to the lensing-CMB cross-correlation, $C_l^{T\psi}$



+ small (but not entirely negligible) δN perturbed expansion effect

(note Rees-Sciama contribution is small, numerical problem with much larger result of Verde et al, Mangilli et al.; see also Junk et al. 2012 who agree with me)

Planck lensing bispectrum detection, $C_l^{T\psi}$



Large cosmic variance and reconstruction noise, but 'detected' at $\sim 2.5\sigma$

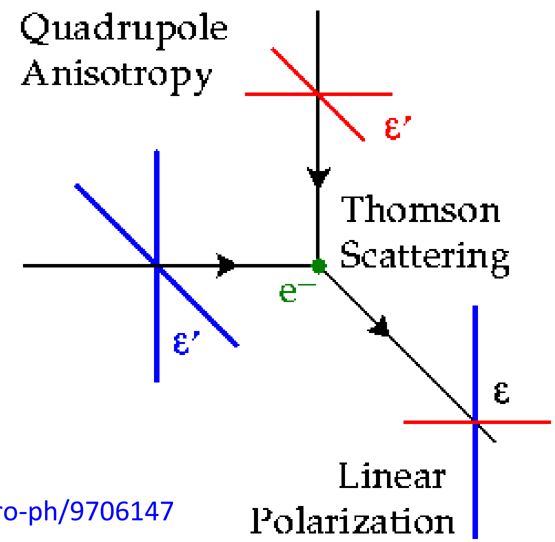
Table 2. Results for the amplitude of the ISW-lensing bispectrum from the SMICA, NILC, SEVEM, and C-R foreground-cleaned maps, for the KSW, binned, and modal (polynomial) estimators; error bars are 68% CL.

	SMICA	NILC	SEVEM	C-R
KSW	0.81 ± 0.31	0.85 ± 0.32	0.68 ± 0.32	0.75 ± 0.32
Binned	0.91 ± 0.37	1.03 ± 0.37	0.83 ± 0.39	0.80 ± 0.40
Modal	0.77 ± 0.37	0.93 ± 0.37	0.60 ± 0.37	0.68 ± 0.39

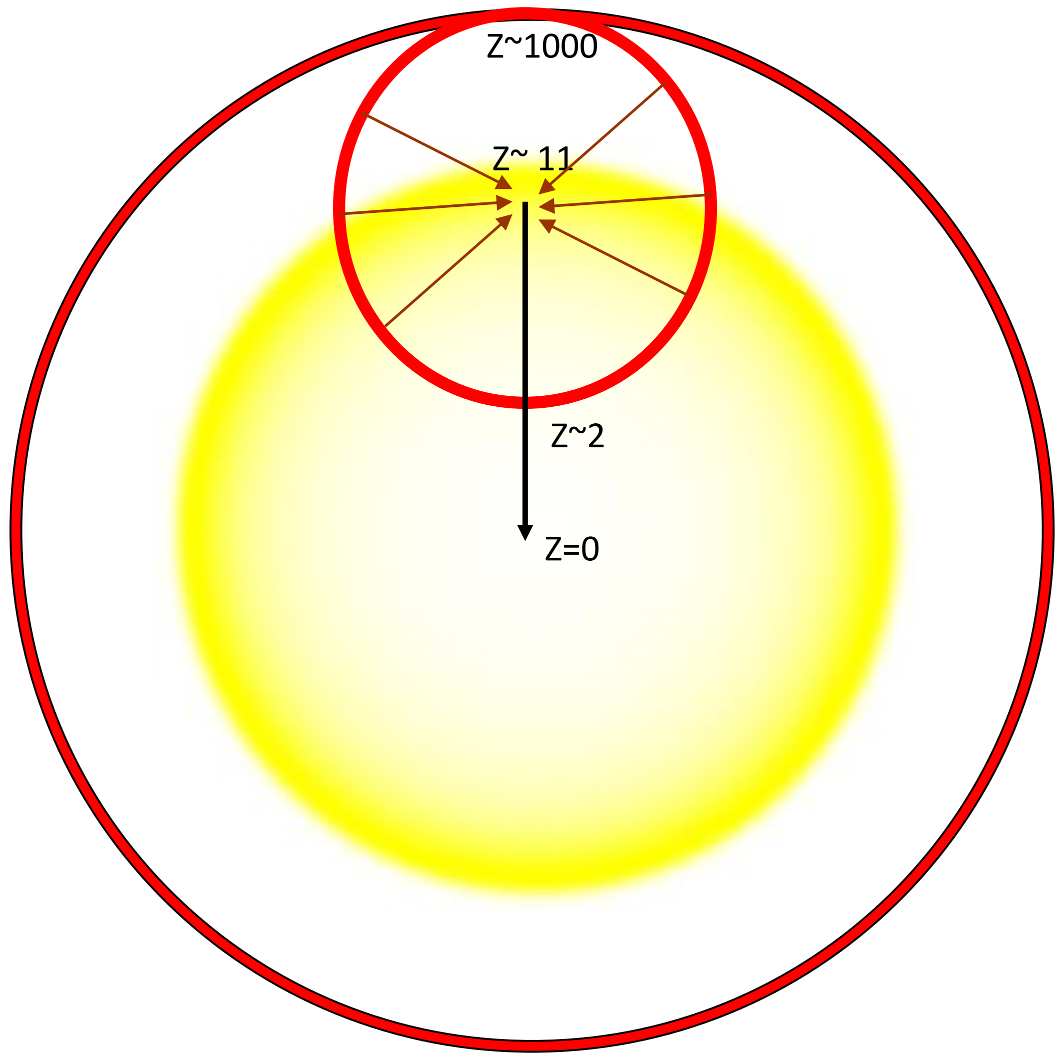
- Importance to separate from f_{NL}

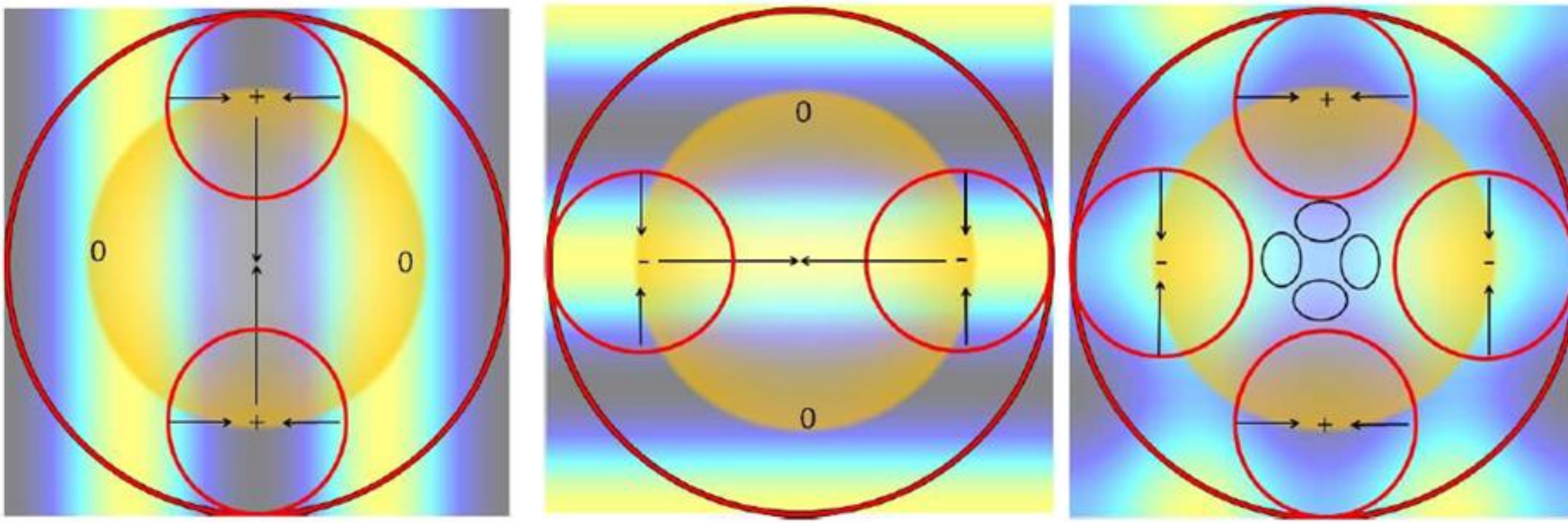
  $\Delta f_{NL} \sim 7$

CMB Polarization – LSS Correlation?



Hu astro-ph/9706147



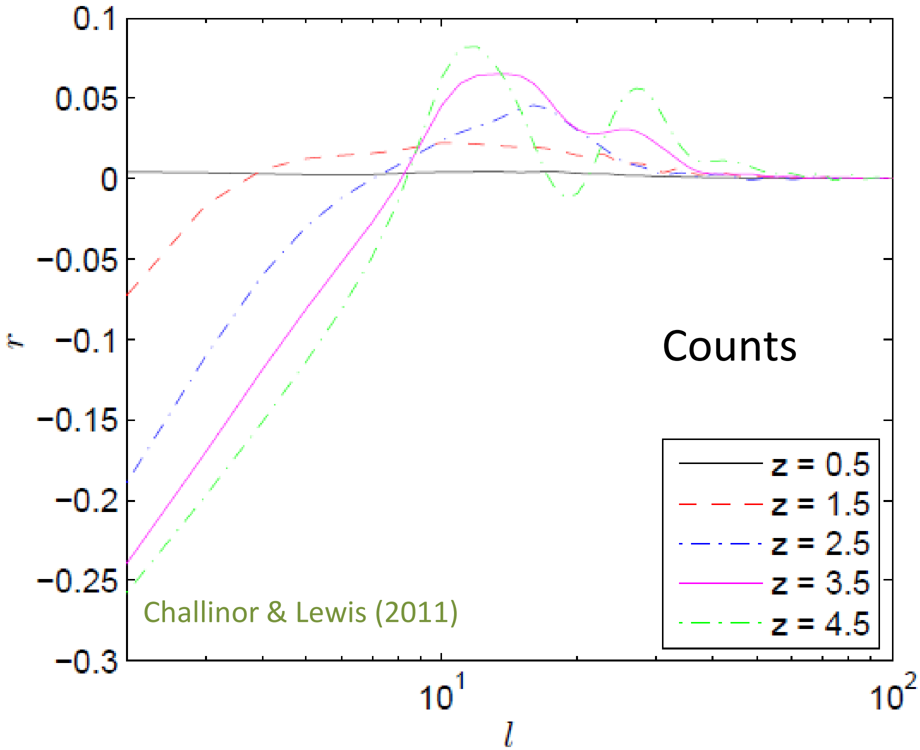


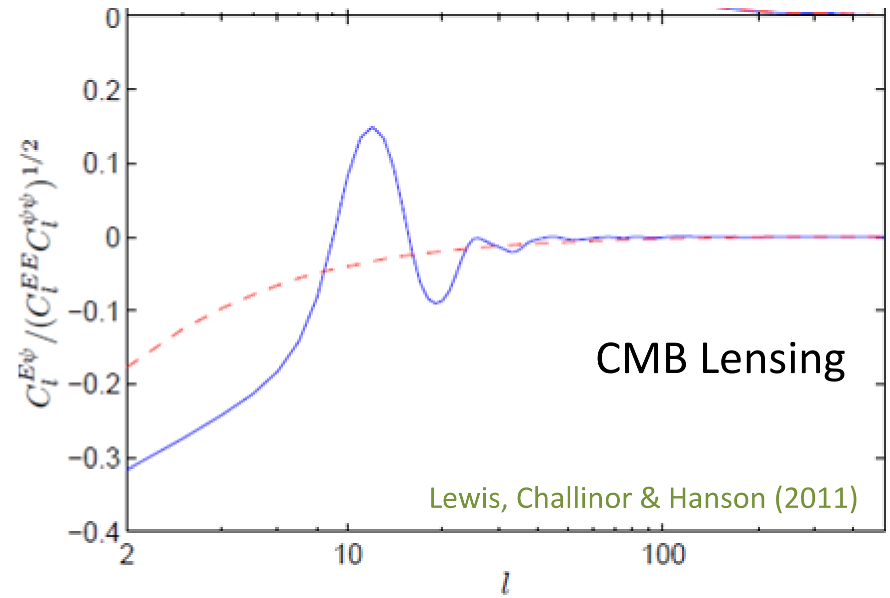
Yes, expect E polarization – LSS correlation on large scales

Lewis, Challinor & Hanson (2011),

CMB polarization-LSS correlation

$$r \equiv C_l^{E\Delta} / \sqrt{C_l^{EE} C_l^{\Delta\Delta}}$$





Number counts at $z < 3$ + CMB lensing gives possible future ~ 6σ LSS-CMB polarization correlation

Rayleigh scattering: Rayleigh × CMB correlations

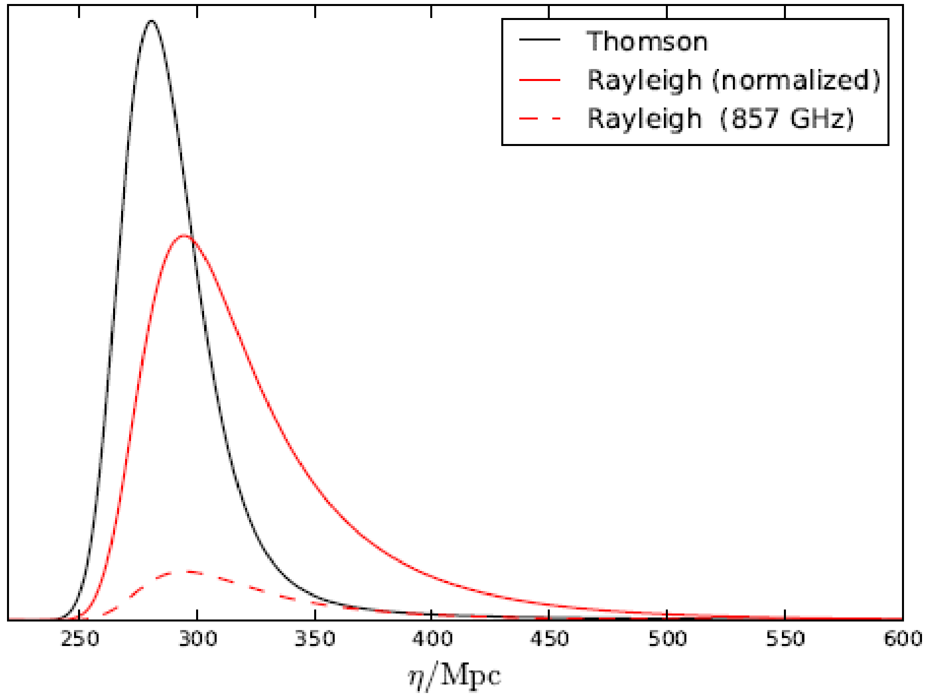
The last-but-one scattering surface: probing baryon LSS at $z \sim 1000$ with multi-tracer CMB

following Takada & Sasaki 1991; Yu, Spergel, Ostriker 2001

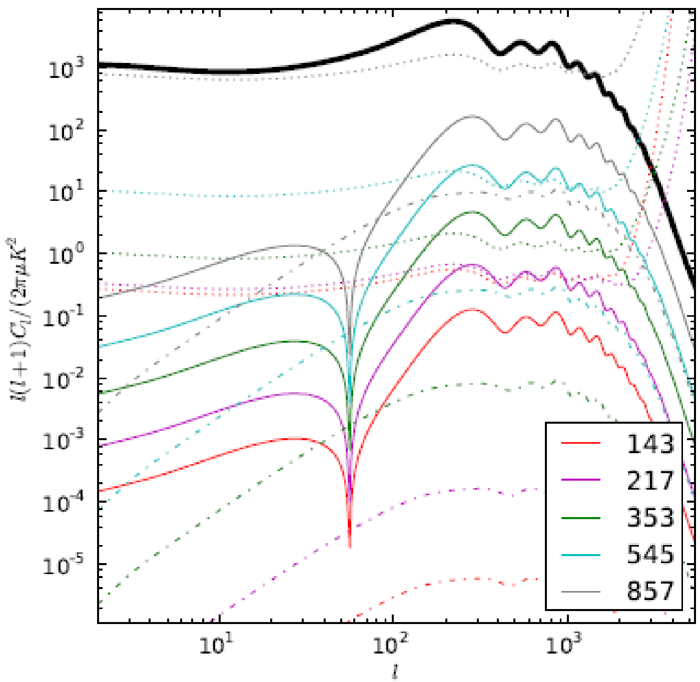
$$\sigma_R(\nu) = \left[\left(\frac{\nu}{\nu_{\rm eff}}\right)^4 + \frac{638}{243}\left(\frac{\nu}{\nu_{\rm eff}}\right)^6 + \frac{1626820991}{136048896}\left(\frac{\nu}{\nu_{\rm eff}}\right)^8 + \ldots\right]\sigma_T$$

Lee, 2005 $\nu_{\rm eff} \equiv \sqrt{8/9}\,cR_A \approx 3.1 \times 10^6\,{\rm GHz}$

Visibility functions



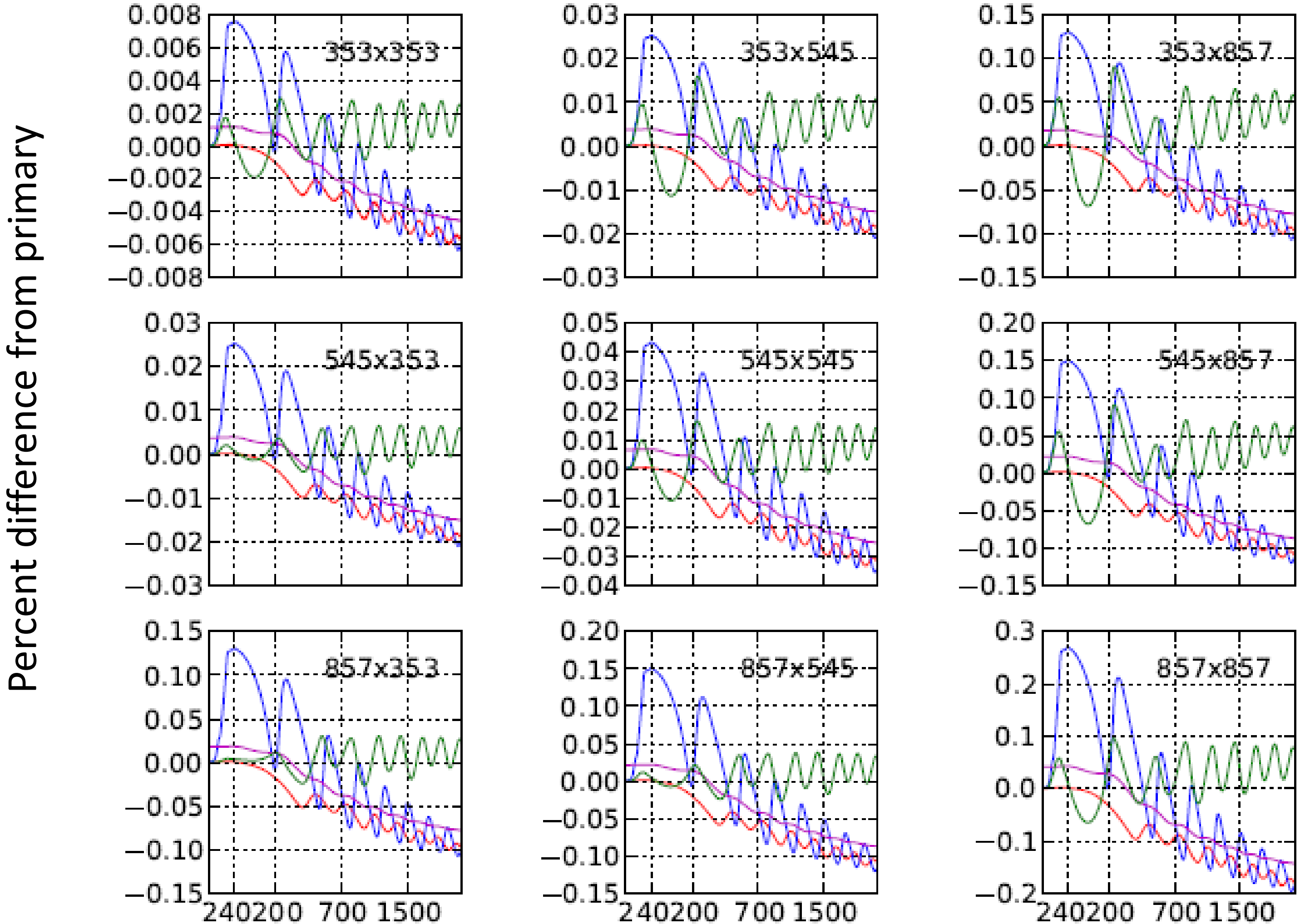
T × Rayleigh power spectra



Temperature and polarization power spectrum at high frequencies

[note detectability of Rayleigh signal only limited by noise (same CMB fluctuations)]

TT, EE, TE, BB cross-frequency power spectra



May be detectable with Planck; large-signal with any future Pixie/Core/PRISM-like mission.

Conclusions

- $TT\Delta$, $TT\phi$ CMB-LSS correlators (bispectra) are significant

  - First full-sky lensing reconstruction from TT with Planck

  - $TT\Delta$ detected at high significance, both counts and CIB

  - TTT Temperature bispectrum mainly from ISW-ϕ correlation

    - now detected at 2.5σ

    - important to model accurately for non-Gaussianity studies

- Also E- LSS correlators (up to $\sim 6\sigma$ cosmic variance limit), not detected yet

- Frequency dependent Rayleigh C_l - may be detectable with Planck, easily in future at high σ

  - very good consistency check on foreground and recombination modelling/BAO, + lensing separation

Rayleigh scattering from tensor modes